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Effects of tunnel design characteristics on driving behaviour and traffic safety: a literature review

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Een belangrijke factor die rijgedrag en verkeersveiligheid kan beïnvloeden is de overgang van de open weg naar de tunnel. Onverwachte veranderingen in het ontwerp kunnen abrupte veranderingen in het rijgedrag oproepen. Met name het de overgang in de hoeveelheid licht buiten en binnen de tunnel is vrij abrupt en grote verschillen moeten vermeden worden. Ook worden overgangen gekenmerkt door een meer beperkte manoeuvreerruimte als gevolg van de aanwezigheid van een tunnelwand of de afwezigheid van een vluchtstrook, wat laterale positieveranderingen en een reductie in rijsnelheid uit kan lokken. Geleidelijke overgangen moeten voldoende tijd bieden om de automobilist aan de nieuwe situatie te laten wennen. Het inrijden van een tunnel mag de onzekerheid van een bestuurder niet vergroten. Voldoende zichtafstanden en anticipatie op het verloop van de weg en de verkeerssituaties kunnen deze onzekerheid beperken. Angst of discomfort bij het rijden in een tunnel kan worden ervaren door angst voor het instorten van de tunnel en onzekerheid over ontsnappingsmogelijkheden. Daarom is het belangrijk goede nood-, evacuatie- en ontsnappingsfaciliteiten te bieden. Angst kan ook verminderd worden door het informeren van de weggebruiker, bijvoorbeeld door middel van incident management, met name in lange tunnels. Tunnelontwerpaspecten die hinder voor de weggebruiker veroorzaken, zoals de aanwezigheid van een flikkerend licht, moeten zo veel mogelijk vermeden worden. Hinder kan ook ervaren worden door een grote hoeveelheid stimulatie in de visuele periferie. Weggebruikers hebben de neiging een zodanige snelheid en laterale positie te kiezen dat de waarde van 2 rad/s niet wordt overschreden. Het is belangrijk deze informatie in gedachten te houden bij het ontwerpen van een tunnelwand en het interieur. Als laatste is de complexiteit van de verkeerssituatie van groot belang voor verkeersveiligheid. Wanneer er veel informatie geboden wordt of een verkeerssituatie vrij complex is, moeten weggebruikers hun aandacht over meer items verdelen, hetgeen tot een onveilige situatie kan leiden.
Om tot een complete basis te komen voor aanbevelingen voor tunnelontwerpcriteria moeten een aantal aspecten nader onderzocht worden. Er is slechts een beperkte hoeveelheid kennis beschikbaar over het effect van lange tunnels op rijgedrag. Daarnaast is niet bekend in hoeverre het in tunnels hanteren van minder strenge ontwerpcriteria, zoals voor hellingspercentage en verhardingsbreedte, verantwoord is in termen van verkeersveiligheid. Ook zijn er geen gegevens beschikbaar over in- en uitvoegingen in tunnels en is er niet veel onderzoek gedaan naar angst of discomfort bij het rijden in tunnels.

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Due to financial and technical considerations, the design of road tunnels often differs from open road design. Standards are applied more loosely, which leads to suboptimal design solutions in terms of traffic safety and comfort. This may affect the level of driving safety for instance if the design provokes sudden changes in driving behaviour, and does not permit sufficient anticipation.
This literature review provides an overview of the effect of tunnel design characteristics on road user behaviour, and can serve as a basis for recommendations on specific tunnel design standards. Various tunnel design characteristics are discussed with respect to their effect on driving behaviour. Tunnel entrances are of special interest, since they confront road users with the transition from open roads to tunnels. To provide safe driving conditions, precautions should be taken to make this transition as smooth as possible. Besides this, the amount of fear and discomfort drivers experience should be minimised and anticipation of upcoming traffic situations should be allowed. Although the focus is on tunnels on motorways, literature of tunnels on other road categories outside the built-up area is discussed as well to provide a more extensive view on tunnel related problems. The effects of lighting, proximity of tunnel wall, lane width, tunnel length, the longitudinal profile, road signs, road markings, emergency lay-bys, and entries and exits will be discussed successively in terms of their effect on driving behaviour. This knowledge can then be used to optimise current design criteria. Finally, an overview is provided of remaining issues that need thorough investigation in future research in order to come to optimal standards for tunnel design.

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SUMMARY

Due to financial and technical considerations, the design of road tunnels often differs from open road design. Standards are applied more loosely, which leads to suboptimal design solutions in terms of traffic safety and comfort. This may affect the level of driving safety for instance if the design provokes sudden changes in driving behaviour, and does not permit sufficient anticipation.

This literature review provides an overview of the effect of tunnel design characteristics on road user behaviour, and can serve as a basis for recommendations on specific tunnel design standards. Various tunnel design characteristics are discussed with respect to their effect on driving behaviour. Tunnel entrances are of special interest, since they confront road users with the transition from open roads to tunnels. To provide safe driving conditions, precautions should be taken to make this transition as smooth as possible. Besides this, the amount of fear and discomfort drivers experience should be minimised and anticipation of upcoming traffic situations should be allowed. Although the focus is on tunnels on motorways, literature of tunnels on other road categories outside the built-up area is discussed as well to provide a more extensive view on tunnel related problems. The effects of lighting, proximity of tunnel wall, lane width, tunnel length, the longitudinal profile, road signs, road markings, emergency lay-bys, and entries and exits will be discussed successively in terms of their effect on driving behaviour. This knowledge can then be used to optimise current design criteria. Finally, an overview is provided of remaining issues that need thorough investigation in future research in order to come to optimal standards for tunnel design.

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Soesterberg

Effecten van tunnelontwerpkenmerken op rijgedrag en verkeersveiligheid: Een literatuurstudie

M.H. Martens en N.A. Kaptein

SAMENVATTING

Om financiële en technische redenen wijkt het ontwerp van wegen in tunnels vaak af van dat van open wegen. Ontwerpnormen worden vaak minder streng toegepast, hetgeen leidt tot suboptimale ontwerpoplossingen met betrekking tot veiligheid en comfort. Dit kan de verkeersveiligheid beïnvloeden, bijvoorbeeld indien het ontwerp plotselinge veranderingen in rijgedrag uitlokt of anticipatie onvoldoende mogelijk maakt.

Deze literatuurstudie geeft een overzicht van het effect van tunnelontwerpkenmerken op rijgedrag en kan dienen als basis voor aanbevelingen ten aanzien van specifieke normen voor tunnelontwerp. Verschillende tunnelontwerpkenmerken worden besproken met betrekking tot hun effect op rijgedrag. Tunnelingangen verdienen speciale aandacht aangezien weggebruikers hier geconfronteerd worden met de overgang van open weggedeelten naar tunnels. Om een veilige verkeerssituatie te kunnen bieden moeten maatregelen genomen worden om deze overgang zo geleidelijk mogelijk te maken. Daarnaast moet de hoeveelheid angst en discomfort die weggebruikers ervaren zoveel mogelijk beperkt worden en moet anticipatie op naderende verkeerssituaties mogelijk zijn. Hoewel de aandacht gericht is op tunnels op autosnelwegen wordt ook literatuur over tunnels op andere wegcategorieën buiten de bebouwde kom besproken om een meer uitgebreid beeld van de problematiek rond tunnels te schetsen. De effecten van verlichting, de nabijheid van de tunnelwand, rijstrookbreedte, lengte van de tunnel, het lengteprofiel, bebording, wegmarkeringen, noodparkeerhavens en in- en uitvoegingen zullen achtereenvolgens bediscussieerd worden in termen van effecten op rijgedrag. Deze kennis kan dan gebruikt worden om huidige ontwerpcriteria te optimaliseren. Tenslotte wordt een overzicht gegeven van ontwerpaspecten, die in de toekomst grondig onderzocht moeten worden om tot optimale normen voor tunnelontwerp te komen.

1 INTRODUCTION

One of the major concerns in current road design is the high level of traffic unsafety caused by human error. Estimations suggest that over 90% of all traffic accidents is related to human error, which indicates that it is important to adjust road design to the limitations of human information processing (Theeuwes, 1994). Characteristics of the road lay-out determine the level of road safety to a large extent. To limit the number of accidents due to human error, general design standards have to be available that take human factors considerations into account. This holds especially true for motorway design, since on motorways high speeds are allowed. Higher speeds increase the chances of exposure to dangerous situations, and impose restrictions on the time available to respond properly in case of unexpected situations.

Some European countries plan to build long stretches of tunnels on motorways in the near future, since building motorways underground has several advantages. The building of roads underground reduces the level of both noise and pollution and the aesthetical value of the environment will not be affected by the presence of a road. However, introducing tunnels can not be done without any further considerations, since driving in tunnels differs from driving on open roads. Tunnels create a sense of narrowness, luminance is limited, and sight distances are restricted. To guarantee a certain level of safety in tunnels, it is necessary to assess to what extent standards for general motorway design should be applied strictly to motorway tunnels as well, to what extent it is acceptable to deviate from standard motorway design criteria, and whether additional tunnel requirements should be specified.

This literature review is a result of the European SAFESTAR-project RO-96-SC.203 (Safety Standards for Road Design and Redesign). The overall objective is the development of general and specific road design standards in order to come to a safe traffic system. This literature review is part of work package 2, that aims at supporting design standards for tunnels on motorways, and provides a survey of available literature regarding the effect of tunnel design characteristics on road user behaviour. This survey serves as a basis for recommendations on tunnel design standards.

In the ideal situation, the level of traffic safety on motorways should not diminish in and near tunnels. Yet, it has been shown that there is an increased accident rate near tunnels, which indicates that current tunnel design is not optimal (Amundsen, 1992). This high accident rate compared to open roads can at least partially be explained by changes in driving behaviour in the approaching area of tunnels. Individual drivers respond to tunnels in different ways, which reduces homogeneity of the traffic flow. Some studies find a reduction in driving speed (Amundsen, 1992; Bampfylde, Porter & Priest, 1978; Chiyoda, 1995; Theeuwes, Van der Horst, Hoekstra & Kaptein, 1995; Gallagher, Freedman & Schwab, 1979), whereas others show a change in lateral positioning (Blaauw & Van der Horst, 1982; Blaauw & Leebeek, 1974; Theeuwes et al., 1995), an increase in steering activity (Theeuwes et al., 1995) and an increase in fear (Christensen, Sætre, Sætre & Beckman, 1993; Amundsen, 1992). In itself, changes in driving behaviour do not have to affect safety. Changes in position or driving

speed do not have to reduce safety, as long as other road users are not involved. However, if other traffic is present and reacts differently, homogeneity of the traffic flow is reduced. Consequently, drivers have to pay more attention to the driving task. If drivers do not increase the amount of attention sufficiently, this may lead to reductions in traffic safety (e.g., Van der Horst, 1990).

Tunnels should be designed in such a way that the level of safety in and near tunnels is about the same as on other parts of the road network. Therefore, it is important to identify the reasons for the low safety level in and near tunnels. The purpose of this literature review is to identify characteristics in tunnel design that deviate from open road design criteria, and may lead to unsafe situations or unsafe driving behaviour in tunnels. Although the focus is on tunnels on motorways, literature on tunnels on other road categories outside the built-up area is discussed as well to provide a more extensive view on tunnel related problems. The effects of lighting, tunnel wall and lane width, tunnel length, the longitudinal profile, road signs, road markings, emergency lay-bys, and entries and exits will be discussed successively in terms of their effect on driving behaviour. This knowledge can then be used to optimise current design criteria. On the basis of the literature review, gaps in current knowledge on tunnel design characteristics will be identified. In order to obtain a complete specification of safety standards, further research will be required.

2 TUNNEL DESIGN CHARACTERISTICS

2.1 Lighting

Road users need to perceive all relevant visual information from a sufficient distance in order to anticipate the driving situation timely. When entering a tunnel, a rather large reduction in ambient luminance may cause problems in perceiving crucial visual information inside the tunnel. Due to this limitation in perception, crucial information may be missed and dangerous situations might result.

When entering tunnels, there are two factors—an adaptation process and the amount of straylight—that limit visual perception of obstacles inside a tunnel.

A slow adaptation process of the visual system occurs when luminance levels decrease. The eyes need some time to get adapted to the lower luminance level, and in this period of time only objects with a luminance not far below the adaptation level outside the tunnel can be perceived. In extreme cases this decrease in luminance can be so large and so sudden that for some time nothing can be perceived at all (Schreuder, 1964a). This may lead to serious problems if there is other traffic or an obstacle in front of the driver that cannot be perceived due to this delay in the adaptation process. This is especially a problem at entrances of

relatively long tunnels, since then the luminance level is generally low, as no extra light from the other end (exit) of the tunnel is coming in.

When approaching a tunnel, perception is also limited due to the amount of straylight in the eye of the driver. Straylight is a constant veil that results from the light that gets scattered in the eye media, in the atmosphere and on the windshield of automobiles. This straylight forms a luminous veil that reduces the visibility of objects in the entrance of tunnels (Schreuder, 1990; Padmos, 1984). This plays an important role especially at tunnel entrances, since the presence of high ambient luminance levels near a dark tunnel entrance emphasizes the relative difference and reduces the contrast of objects in the tunnel. Before entering the tunnel, the driver's fovea is adapted to the sum of the luminance of the surrounding area and the amount of straylight in the eye of the driver (Narisada, 1986). As a consequence, visibility problems inside a tunnel are likely to occur, unless the luminance level inside a tunnel is high enough.

Due to the slow adaptation process and the presence of straylight, the luminance level inside the tunnel may appear to be extra low and, consequently, the tunnel appears as a black hole, in which no details can be perceived. This will result in increased driver uncertainty of what to expect when entering a tunnel. Uncertainty does not directly affect traffic safety, but increased uncertainty is likely to result in changes in driving behaviour, which may lead to reductions in traffic safety. In addition, the limited visual perception may directly lead to a reduction in safety. Due to a lack of anticipation, the risk of rear-end collisions increases, and due to limited visual guidance, lane keeping might be difficult.

Quite some research has been done on lighting in tunnels and its effect on human performance. Schreuder (1964a) set up a laboratory experiment to investigate what lighting contrast outside and inside the tunnel would be best for the perceptibility of objects in a tunnel. In this experiment, an observer had to face a large screen of variable luminance L_1 (representing the luminance level of the pavement in front of the tunnel entrance) wherein for only 0.1s a rectangular opening was presented, showing a lower luminance L_2 (representing the luminance level of the threshold zone). In the centre of the opening the observer had to perceive an object of various contrasts. The results suggested that a contrast of 0.2 between the luminance of the object (L_3) and luminance of the background—defined by $(L_2-L_3)/L_2$—would be necessary to allow for sufficient perception. It was concluded that, in order to realize this, the entrance luminance of a tunnel, as represented by L_2, should be at least 0.1 of the screen luminance L_1. Yet, in the experiment, L_1 was restored after exposing the observer for 0.1 s to the simulated tunnel opening to preserve adaptation to the screen luminance. This situation does not correspond to the actual conditions on the road. Road users start to concentrate on the dark tunnel opening from a distance of approximately 150 m to 200 m from the entrance (Narisada & Yoshikawa, 1974; Verwey, 1995), so the tunnel opening becomes a permanent part of the visual field. This implies that even before entering the tunnel, the process of foveal adaptation begins, decreasing the adaptation level of the eyes even outside the tunnel. Since in this experiment Schreuder did not take this factor into

account, his findings may have led to the recommendation of higher luminance levels inside tunnels than actually required.

Kayser and Pasderski (1991) investigated the effect of different ratios of lighting levels inside and outside a tunnel on vehicle speed in a real life driving situation. They made a distinction between different tunnel parts, each with their own pattern of luminance. Despite a large range of differences between the luminance inside and outside the tunnel, no effect was found on driving speed. The distribution of speed differences was about the same for each class of luminance difference (difference in L_a/L_i ratio, where L_a is the luminance the eye is adapted to and L_i is the luminance inside the tunnel), which means that speed was found to be independent of lighting ratio. These observations allow the conclusion that under normal traffic circumstances, driving speed at tunnel entrances is not affected by the lighting ratio that characterizes the transition from light to dark.

Subjective evaluations of safety, with respect to the luminance of various tunnel entrances, were recorded in an experiment by Adrian (1982). The study was carried out in a laboratory setting, using apparatus to simulate tunnel scenes as seen by an approaching driver from 150 m distance. The scenes were created by using large transparent photographs that could simulate varied luminance levels at tunnel entrances. Subjects had to use numbers from 1 (black hole) to 9 (very good viewing conditions) to judge the safety of luminance differences between the exterior and interior of the tunnel. The results showed that a safety rating between fair and good almost equals the target contrast of 0.25. So whether this scaling method or the contrast criterion is used as a basis to determine the L_2 levels, either one will lead to almost the same values.

There are two possible solutions to counteract the loss in visibility at tunnel entrances. One is to increase the luminance level in the threshold zone of the tunnel. The threshold zone begins when the luminance level of the open road preceding the tunnel suddenly drops to a lower level. Throughout the threshold zone, this reduced luminance remains constant. Increasing the luminance level in the threshold zone can be realised by using a high-power lighting installation, placing tunnel portals that allow daylight to come through (Schreuder & Swart, 1993) or by means of counterbeam lighting, which enlarges contrasts and provides good optical guidance (see later in this paragraph). Activating one's headbeams might also reduce the decrease in luminance and increases visibility of road markings. Another way to reduce the visibility problems at tunnel entrances would be to decrease the luminance level just outside the tunnel in order to decrease extreme luminance differences (which may vary from 8000 cd/m^2 outside the tunnel to 15 cd/m^2 inside the tunnel) and resulting adaptation problems. This can be done by using a dark road surface or by planting trees or other high constructions near the tunnel entrance. A combination of the two methods will lead to the best result. It must be kept in mind that, although most problems occur at tunnel entrances, with a transition from high to low luminance, the adaptation at tunnel exits from a low to a high level should not be disregarded. Although this process is relatively fast, very large transitions in luminance should also be avoided near tunnel exits (Schreuder, 1964a).

A rather efficient solution for the transition problems, that uses the principle of slowly decreasing the luminance level inside the tunnel was applied to the Louis Hippolyte Lafontaine Bridge tunnel complex (Branchaud, 1967). This tunnel complex contained a system which varies the lighting intensity progressively. This way, the eyes would gradually adjust to the decreasing intensity levels. Another good example of preventing the visibility problem in tunnel entrances was used in the Silver Creek Cliff tunnel in Minnesota (Boya & Sadowski, 1995). Here, the two possible solutions were combined. In order to reduce large luminance differences, approach pavement and other external features were carried out in dark colours whereas light-coloured tiles were applied to the tunnel's interior walls.

When approaching, entering or driving in a tunnel, it is important to perceive the course of the road, other road users and dangerous obstacles in time. In this respect contrast is particularly important, which led to the development of counterbeam lighting. With counter-beam lighting (also called asymmetrical lighting), the light works primarily opposite to the direction of traffic so that the road surface gets bright and obstacles remain dark, resulting in a better contrast and increased visibility of the contours of objects at tunnel entrances as well as inside the tunnel. Road surface luminance is higher with asymmetric lighting than with symmetric lighting for the same horizontal illuminance, because most road surfaces show a preferential directional reflectance (Schreuder, 1964b, 1967). The combination of a higher luminance level and a larger contrast will result in the same level of visibility for a lower level of illuminance, so for a lower level of installed power, resulting in savings in money and energy. With counterbeam lighting, the light sources, that are aimed against the direction of traffic are highly visible, which results in good optical guidance, especially when approaching the tunnel.

Compared to conventional lighting, there are some disadvantages of using counterbeam lighting. Higher ceilings may be needed since the luminaries are often higher. The fact that the lights are aimed against the direction of traffic will lead to increased glare and sometimes to a more pronounced flicker and glare. Flicker, for instance resulting from periodic luminance changes in the visual field, can be quite disturbing, especially for epileptic drivers. This flicker effect may also be observed with grids or sun screens, designed to let some sunlight pass in order to increase luminance in the threshold zone (Schreuder, 1981; Schreuder & Oud, 1988). With counterbeam lighting it remains to be seen if the visibility of non-stationary, non-flat, non-diffuse obstacles is also better. Object recognition or identification is not always good (Schreuder, 1981), since objects are only silhouettes. Finally, it should be considered that porous asphalt (ZOAB), because of their open structure, can decrease the effect of counterbeam lighting.

In summary, large differences between the luminance level outside and inside a tunnel should be avoided in order to avoid adaptation and perceptibility problems. Luminance differences can be minimized by increasing luminance inside and decreasing luminance outside the tunnel. Here the absolute luminance level inside the tunnel is not of utmost importance, but rather the difference between the luminance level inside and outside the tunnel and the

whether this transition in luminance level is a gradual one. A luminance ratio of 1 inside the tunnel to 10 outside the tunnel is generally considered sufficient for anticipating upcoming situations. An obstacle contrast of 0.25 would suffice, a value that could be realized by using counterbeam lighting or contrast lighting. However, it should be noted that these recommendations are not based on data from real or simulated driving studies, but rather from data of laboratory experiments. The luminance level inside a tunnel should allow for sufficient anticipation of objects and the road lay-out.

2.2 Proximity of tunnel wall and lateral clearance

Due to financial and technical constraints, the lateral clearance in tunnels is often minimized to a degree that is generally considered unacceptable in open road design. Research findings show that the proximity of the tunnel wall to the lane one is driving on, has an effect on perceived narrowness of the tunnel, and consequently on driving behaviour.

The ideal situation would be if lateral clearance within tunnels would not differ from that on open roads. However, if for some reason the design of a tunnel requires limitation of dimensions in some way, there should be enough time for drivers to get used to the new dimensions to avoid any radical changes in driving behaviour. Several studies examined the effect of restrictions in lateral distance on driving behaviour.

In response to a relatively large amount of accidents, Blaauw and Leebeek (1974) examined, among other things, the lateral position of road users at the aqueduct of the motorway RW4, by means of a qualitative analysis of video recordings. They found that in the two-lane tunnel tubes, while driving on the right lane, road users drove more to the left side at the beginning of the aqueduct wall, where the emergency lane was interrupted. This could be an indication of fear to hit the aqueduct wall. The lateral position changed again to the old position of the open road after some adaptation to the decreased available lateral space.

To get a better idea of the underlying mechanism of this change in driving behaviour, Blaauw and Van der Horst (1982) compared the lateral position of drivers in two different tunnels, the Benelux tunnel and the Vlake tunnel in the Netherlands, that only differed in the lateral clearance. About 115 m before the tunnel entrance of the Benelux tunnel, the pavement next to the right driving lane decreased from a width of 4.05 m to 0.80 m. The width remained 4.05 m for the Vlake tunnel, allowing continuous presence of an emergency lane. While approaching the Benelux tunnel, road users monotonously increased the distance to the right side of the road, with a lateral displacement of 0.33 m at the point of the narrowing (115 m before the tunnel entrance), reaching a maximum of 0.70 m at the tunnel entrance. While driving through the tunnel, the lateral position shifts slowly more to the right again and stabilizes at the original mean value of vehicle position on open roads. No systematic lateral displacement was found in the Vlake tunnel. Lateral displacement does not have to reduce traffic safety in itself, but it may decrease safety if, due to the limited space, traffic in the

right lane moves to the left and traffic in the left lane moves to the right. This may lead to interference between traffic in adjacent driving lanes.

In a driving simulator study, Theeuwes, Van der Horst, Hoekstra and Kaptein (1995) investigated the effect of design of a single-lane tunnel tube on driving behaviour. They found an increase in steering frequency and a reduction in driving speed with decreasing road width in the single lane tube. The increase in steering activity suggests that people had to put more effort in keeping the vehicle on the road. This steering behaviour is likely to be found in multi-lane tubes as well, since the lateral displacements, found in all tunnels also require more accurate steering under those conditions. The reduction of driving speed and the increase in steering activity may reveal the fear of hitting the tunnel wall. A narrow tube requires better lane keeping, which is facilitated by a reduction in driving speed. On the other hand, the speed reduction can also be the result of the high amount of stimulation in the visual periphery. Research shows that too much stimulation in the visual periphery (about 30 degrees left and right of the fovea), is considered very unpleasant (Yamanaka & Kobayashi, 1970). If the value of 2 rad/s of angular velocity is exceeded, drivers adapt their position and speed to avoid disturbing effects (Van der Horst & Riemersma, 1984; Blaauw & Van der Horst, 1982). A tunnel wall that is positioned close to the driving lane provides a relatively high amount of visual stimulation. Since changing lateral position does not solve the problem in single lane tubes, reducing speed is the only solution. Again, these changes in driving behaviour do not necessarily reduce safety in tunnels, but a reduction in safety may result. If drivers undercompensate, or do not decrease their speed sufficiently, the driving task still asks for more effort than available, which leads to problems with lane keeping. However if they overcompensate, or decrease their speed more than the task would require, this may lead to a decrease in homogeneity of the traffic flow. In terms of traffic safety, tunnel design should not require compensation in any form.

Several studies investigated the effects of restriction in lateral distance on velocity and headway of cars near tunnel entrances (Bampfylde et al., 1978; Blaauw & Leebeek, 1974; Blaauw & Van der Horst, 1982). Bampfylde, Porter and Priest (1978) examined the relationship between speed and traffic flow in tunnels in the UK and compared the results with those on open roads. They found some evidence that speeds within the various tunnels are somewhat lower than those predicted for open rural roads of similar geometry and traffic composition.

In conclusion, extreme reductions and rather abrupt changes in lateral clearance should be avoided in order to avoid large or sudden changes in driving behaviour. Reductions may result in increased steering activity, lateral displacement and reductions in driving speed, factors that may negatively affect driving safety since drivers may respond in different ways. In order to avoid reductions in homogeneity, and head-on and rear-end collisions, sufficient lateral manoeuvring space should be provided. A smooth transition should be provided between the standard open road, the road part approaching the tunnel and the tunnel entrance, without any sudden narrowing. It is yet unclear to what extent reduced road width in tunnels

is acceptable. Anticipation of the road lay-out seems necessary to prevent uncertainty about the available manoeuvring space and lane width should be sufficient (3.30–3.60 m) to avoid interfering actions from passing cars and to improve the driving conditions for heavy vehicles. Although higher costs are involved, continuing the emergency lane inside a tunnel does not only guarantee a continuous amount of available lateral space, but also permits clearing the road in case of a car break-down, thereby increasing objective and subjective safety (see § 2.7).

2.3 Tunnel length

Driving through tunnels may in itself lead to increased uncertainty and fear. This fear is partly the result of the experienced threat of getting stuck inside the tunnel in case of traffic accidents or calamities, because of experienced vulnerability and doubts on physical safety inside tunnels in these cases (Daanen, Gids, Jansen & Mossink, 1993). In a driver interview on fear in tunnels by Christensen et al., (1993), the two reasons mentioned for tunnel fear are fear of hitting anything, like an object, the tunnel wall or other vehicles, and fear of problems to escape from dangerous situations, for instance in case of a fire or if a tunnel collapses. Due to this latter fear, tunnels that underpass water are considered more fearful than other tunnels.

Amundsen (1992) and Christensen et al. (1993) conducted surveys to assess the factors that influence the amount of fear drivers experience when driving through tunnels. In the questionnaires, people indicated to have more problems with driving in tunnels as the length of the tunnel increases. This can be explained by the fact that if driving in tunnels is considered to be dangerous, driving in long tunnels leads to longer exposure to this dangerous situation. In the Danish survey by Christensen et al. (1993), people indicated that tunnel length affects the amount of fear they experience. About 8% of the respondents indicated to experience strong anxiety, in some cases even leading to phobic feelings. The results may be somewhat biased, since the statements are primarily based on experiences of driving through a tunnel of 20 kilometres in length, a length that does not yet exist in most countries. Moreover, Denmark does not have too many tunnels, so lack of experience in tunnel driving might also have affected the results. In Amundsen's survey, 4% said that they did not like using road tunnels and about 3% said they would prefer to use an alternative route. About 42% of the respondents indicated that they did not consider length to be a problem at all and 2% indicated they did not want to use tunnels over 2 km of length. The problems experienced with length also seem to depend on the design of the tunnel. A long tunnel is acceptable for about the majority of road users if the tunnel contains long stretches without any curves, a small slope downwards at the entrance of the tunnel, and a large slope upwards at the end to exit the tunnel rather quickly. These subjective data indicate that fear in tunnels might be reduced by allowing for sufficient anticipation in long tunnels. Even though the percentage of people that is really scared is rather small, even the presence of this small group can have major implications for the homogeneity and safety of the entire traffic stream.

Although no objective investigations of the effect of tunnel length on driving behaviour are available, one can state that extremely long tunnels should be avoided if possible. A compromise for a tunnel of considerable length is to split the tunnel up in different parts. This way the tunnel may be perceived as a sequence of short tunnels, which may reduce the fear, and therefore limit a possible reduction in safety. Besides the fact that this is not always possible, a disadvantage is that splitting the tunnel up in several short tunnels implies increasing the adaptational problems, with consequences for traffic safety. Providing some information about the total length of the tunnel or its remaining length may also reduce fear, since this reduces the experienced uncertainty. In some countries, information on tunnel depth is also provided. Whether these measures reduce the amount of fear to the extent that traffic safety is no longer jeopardized remains to be seen.

2.4 Longitudinal profile

To ensure a safe driving situation, proper anticipation of upcoming traffic situations, possible accidents or traffic queues and the road lay-out is required. Adequate sight and visibility distances allow drivers to prepare for changes in the road lay-out and traffic situation and reduce uncertainty.

The amount of curvature in a road can have major implications for the possibility to anticipate the longitudinal profile. This applies especially to tunnels, where sight is overall more restricted than on open roads due to the presence of a tunnel tube. The tighter the curve, the more problems will occur with anticipating upcoming situations or responding to preceding traffic. Besides sight distance, tight curves will also affect the amount of effort put into the driving task. There will be more problems with lane keeping, which can either affect driving behaviour directly, or indirectly by affecting driver uncertainty. Rising and falling gradients inside tunnels are also important in this respect, since they decrease the possibility to look through the tunnel, reduce sight distances, and limit anticipation. Besides this, gradients affect driving speed via characteristics of the car, with rising gradients leading to lower speeds and falling gradients to higher speeds. The combination leads to rather large variation in driving speed. Speed differences lead to reductions in traffic homogeneity and affect driving safety in that respect too.

A study by Kaptein and Theeuwes (1996) assessed the design of a tunnel to be built on motorway RW14 near Voorburg, the Netherlands, with special attention paid to sight distances. The tunnel, consisting of a two-lane tube in each driving direction, had to be interrupted twice by intersections at open road level. The design speed was 70 km/h, but reducing the design speed to 50 km/h in the area between the two intersections was being considered. The questions that needed to be answered were concentrated on sight distances at the intersections and the overview on RW14 when coming from a minor road, waiting to merge into or cross the traffic stream on RW14. Criteria used to evaluate the situation were driving sight (sufficient sight distance to anticipate the course of the road or changing

situations) and stopping sight (sufficient sight distance to stop completely when a dangerous object or situation is detected, Godthelp & Tenkink, 1990). Taking a maximum acceptable deceleration of 2.5 m/s^2 (Cleveland et al., 1985) and a reaction time delay of 2 seconds into account, the proposed design did not provide enough driving sight nor sufficient stopping sight for drivers to anticipate because the tunnel tubes were built too close to the intersections. This held true for traffic on RW14 as well as for traffic driving on the minor road, crossing the RW14.

It is important to choose a speed limit that is in accordance with the driving and stopping distances, but indicating a speed limit alone does not guarantee that this is also the actual driving speed. Therefore, the behavioural consequences of the design of the RW14 tunnel were investigated in a driving simulator study (Kaptein, Theeuwes & Hoekstra, 1996). The results showed that road users drove much faster than the indicated speed limit, due to the impression provided by the general road lay-out. The road seemed to be a motorway, and according speeds were observed. This high speed caused dangerous driving situations such as strong braking behaviour and short Time-To-Collisions (TTCs), which indicates the amount of time before a collision would occur if driving behaviour is not changed.

In order to examine whether a change in the road lay-out would reduce driving speed, a second behavioural simulator study was conducted (Kaptein, Martens, Theeuwes & Hoekstra, 1996). The effective road width and amount of visual guidance was reduced by applying 0.70 m wide road metal strips instead of side markings. The amount of visual guidance was also reduced by using a tunnel wall pattern with a non-regular texture. These measures resulted in a large reduction in driving speed (up to 15 km/h), thereby increasing TTCs (leading to safer driving conditions) and reducing the amount of strong braking behaviour. By reducing actual driving speed, sight and stopping distances corresponded better with the accepted criteria.

Under some circumstances, a tunnel, that may be well designed in terms of exact dimensions may not be so optimal after all. Specific characteristics of tunnels may lead to illusions and a perception of dimensions that does not correspond to the actual dimensions. Besides non-optimal objective measures, subjective impressions may also lead to reductions of traffic safety.

A typical example of a visual illusion, or a subjective perception that does not correspond with the objective situation, is provided by Leeuwenberg and Boselie (1980). They analysed the visual aspects of the longitudinal profile of the eastern tube of the Schiphol tunnel in the Netherlands. Before entering the Schiphol tunnel on the east side, the road has a rising gradient. Therefore, it is difficult to anticipate the course of the road. After entering the tunnel, the road has a falling gradient. Normally when going downhill, one gets a clear overview of the road, but in tunnels, due to a restriction in height, this overview may be rather limited. For the Schiphol tunnel this is particularly true, since the road surface is also very dark. The ceiling, that is strongly decreasing in height will either create the perspective-illusion (suggesting that the road gets smaller whereas its actual width does not change) or a

rising-gradient-illusion (it seems like the road contains a rising gradient when actually the ceiling is just getting lower). Since perceived road width has an effect on driving speed (Tenkink, 1989), the perspective-illusion may lead to a decrease in speed and to braking behaviour. Together with the wall structure, that emits light every 130 cm and thereby confronts drivers with a high frequency of changing light, this may possibly lead to a fast driving illusion. Because of these factors, the eastern entrance of the Schiphol tunnel may result in poor safety conditions if drivers expose unexpected braking behaviour and anticipation of dangerous objects or situations is hardly possible.

Conclusions from the study by Leeuwenberg and Boselie are to aim for a gradual transition in perceived height and width and to choose an appropriate luminance level inside the tunnel in order to prevent visual illusions and to provide the driver with a more accurate impression of the lay-out of the tunnel. Visual illusions should be avoided, since drivers perceive something that does not correspond to the real situation. With respect to anticipation in the longitudinal direction, tight curves and large gradients should be avoided in tunnels, because of the indicated problems. However, if, for some reason, sight distances are restricted, some additional precautions should be taken. Lowering the speed limit may help to some extent, although additional measures might be required to assure that drivers comply with this restriction in driving speed. The presence of an incident management system, that indicates when a lane cannot be used once a non-moving vehicle is detected, may to some extent make up for short viewing distances (Van der Horst & Theeuwes, 1993). This way, auxiliary information compensates for a reduction of the anticipation distance that drivers normally need. But whenever possible, driving sight and stopping sight should be sufficient for every particular driving situation per se, without any concessions.

2.5 Road signs and signals

In general, motorways show a large number of road signs to indicate destinations, bottlenecks, road numbers, rest areas, and tunnels. Sufficient information should be provided in order to let drivers reach their destination in an efficient and safe manner, although this should not lead to an overload of information. If too much information is provided, drivers have to divide their attention over a too large number of sources and driving safety may be reduced, since not enough attention can be put into the driving task itself.

Research has shown that road users focus their attention on the tunnel entrance some time before actually entering the tunnel. Narisada and Yoshikawa (1974) showed that during the last 150 m before entering a tunnel, relatively many eye fixations are directed to its entrance. In addition, Verwey (1995) showed that on motorways the eye blink frequency decreases about 200 m before the tunnel entrance. Attention is focussed on the tunnel entrance, which means that the environment in front of the tunnel should not ask for special attention. If there is too much information in the area close to the tunnel entrance, information will either not be noticed or attention, normally paid to the tunnel entrance, will be distracted. Therefore, a

proper treatment of lateral areas near the tunnel is very important. It should provide a calm and comprehensible picture to drivers in order to allow them to focus their attention to the tunnel entrance. The use of road signs near tunnel entrances should be reduced to a minimum and they should not be erected immediately (150-200 m) in front of a tunnel.

Besides placing signs in front of a tunnel, it may sometimes be necessary to use road-signs inside a tunnel, for instance in case of sharp curves or to indicate an upcoming exit. Problems with signs inside a tunnel tube may occur due to limited visibility and readability distances. Tunnels have rising and falling gradients and curves, which reduces viewing distances and readability distance and may thereby limit the time available to read and process the information on these signs. Besides visual problems, there may be problems with placing signs, due to limited tunnel height. A possible solution for such non-optimal situations is provided by Campbell (1967). The idea was to put illuminated signs on the ceiling, stretched out like signs on the pavement. A 14.6 m long sign, 3 m wide was placed on the ceiling, backlighted and tested and reactions have been favourable.

Since visibility distances are restricted, sufficient anticipation is not always possible and serious problems may result. Therefore, signals may be used to indicate any deviant situation, like non-moving vehicles inside the tunnel. This can be done by using an incident management system, that indicates which lanes can be used and which can't. Schmarsel, Von Stein, Kaemmerer and Steimann (1970) reported on the experiences after half a year of use of the Rheinallee tunnel. In this tunnel, incident management was installed, using detectors, television equipment, signals, traffic signs. When a car breaks down inside a tunnel, this may create a dangerous situation, especially if there is no emergency lane available. Therefore, it seemed necessary to use a system that provides information to other drivers in case of a problem. To guide the traffic, signs that can display green arrows (indicating a free driving lane), yellow arrows (indicating a necessary lane change) or red crosses (driving on this lane prohibited) are used above each lane. There are no experimental data available, but subjective evaluations of the system have been favourable, with drivers indicating good perceptibility of the signs (even though the dimensions are small), a straightforward meaning and appreciation of the various possibilities per driving lane. Other examples of incident management are found in the Louis Hippolyte Lafontaine Bridge tunnel and the St. Gotthard tunnel (17 km), where the system is intended to alleviate the strain imposed on motorists driving long tunnels. Access is controlled by signals at both ends of the tunnel while traffic lights and speed limit signs are provided regularly.

Besides incident management, another way to increase traffic safety is to provide information about dangerous features of the tunnel. One way to do this is to provide specific information about special route features and the required driving behaviour. For instance in the rural road tunnel of Mont-Blanc/Le Fayet (20 km), safety problems occurred for two reasons. Firstly, problems occurred with inexperienced drivers who lack the know-how of how to drive in tunnels with steep grades and tight curves, which leads to inappropriate braking patterns. Secondly, time pressure led to the acceptance of unnecessary risks by professional and

experienced drivers (Têtard et al., 1993). Providing some extra information about the presence of upcoming curves and gradients and some indication of the most optimal driving behaviour may therefore prevent unnecessarily unsafe situations. Unfortunately, no evaluations are available. This example is rather specific, since generally tunnels on motorways will not have very tight curves, but the principle can also be applied to motorway tunnels, especially where dangerous driving behaviour often occurs. Besides signs, indicating problems, one could also think of a sign indicating that the situation is safe. In Amundsen's (1992) survey, people reported that a sign indicating the situation in the tunnel is safe would reduce their anxiety, also because the presence of this message would indicate that the tunnel is being monitored.

Taken together, these results suggest that some additional attention must be paid to the driving task when approaching tunnels, since the driving situation changes. Research suggests that drivers, approaching a tunnel, pay a relatively large amount of attention to the tunnel entrance. This information can be interpreted in two different ways. One interpretation is that placing signs or signals immediately in front of a tunnel entrance would lead to situations where drivers simply do not perceive these signs, since their (visual) attention is attracted to the tunnel entrance. This may lead to a reduction in driving safety, if people miss information they need, for example if drivers do not notice the sign indicating an exit right behind the tunnel, they will not be prepared for the exit, and may need to perform two lane changes within a 100 m. Another interpretation is that erecting a road sign in direct proximity to the tunnel wall will distract the driver's attention from the tunnel wall, so that the driver insufficiently anticipates the demanding task of entering a tunnel. No research results are yet available that examine the effect of information within the last 200 m before entering a tunnel. The fact that drivers direct their attention to the tunnel entrance from 200 m before the tunnel entrance, does not have to imply that it is required to do so. It might be the case that this is just the result of the conspicuity of the tunnel entrance. Although the increased accident rate in the threshold zone of current tunnel design, compared to the interior of the tunnel, may suggest that entering a tunnel is quite demanding, further research must be conducted to investigate this. Optimal tunnel design may not require that attention needs to be paid exclusively to the tunnel entrance. Until further research is conducted, it is advised that placing signs and signals immediately in front of a tunnel entrance is avoided. Signs and signals inside the tunnel can also be used, but in this case special attention must be paid to the visibility and readability distances. Due to restriction in height, placing road signs in tunnels might cause some problems. However, creative solutions might solve this problem. Besides general road signs, incident management can be used inside tunnels to inform the driver. In case of a problem, traffic may be guided and lane use can be controlled. A sign, indicating the tunnel is safe, would be useful in reducing drivers' anxiety.

2.6 Road markings

The presence of road markings is important for the driving task, since it allows for accurate steering and provides the opportunity to anticipate the course of the road. Tunnel walls, painted in a light colour may provide some visual guidance, but road markings are of utmost importance in this respect, resulting in reduced driver uncertainty. Due to these characteristics, road markings may lead to relatively high driving speeds, something that may reduce traffic safety because it may increase the chances of exposure to dangerous situations, and impose restrictions on the time available to respond properly to unexpected situations. However, overall, road markings are assumed to enhance traffic safety despite this effect on speed. Although most research on road markings deals with road markings on open roads, findings may also have implications for road markings in tunnels.

In tunnels, due to restrictions in sight distances and a relatively low level of luminance, the presence of road markings is especially helpful to provide information about the course and lay-out of the road. The majority of road marking principles of open roads also applies to tunnels, but road markings in tunnels require some special attention. Visibility of road markings may be difficult in tunnels, especially with low luminance levels and in rainy conditions, where the road surface, dependant of tunnel length, can sometimes be almost as wet as the surface on open roads. With reduced visibility of road markings, the accuracy of steering behaviour may be impaired. Increasing the level of luminance inside a tunnel increases the visibility distance of road markings considerably (Van der Horst & Alferdinck, 1997). Activating the headbeams inside tunnels may also increase these visibility distances. Especially at tunnel entrances, where increased steering activity and lateral displacement are found, information about the edge lines of the driving lanes and the course of the road is of utmost importance in terms of traffic safety. By providing good visual guidance in the entrance, the reductions in driving speed sometimes found near tunnel entrances might be forestalled.

Schreuder (1991) recommended to use profiled road markings in tunnel entrances, especially in curves, to allow for better lane keeping. If low luminance and wet road surface prevent optimal perception of conventional road markings, profiled road markings improve visibility of the markings under these circumstances (Blaauw, Padmos, Alferdinck & Hoogeweg, 1983; De Vos, Van der Horst & Bakker, 1996), allowing better anticipation on the course of the road, more accurate lane keeping, and more accurate steering. In addition, information about the road lay-out is provided if drivers tend to cross the markings.

Some extra help with anticipating the course of the road may be provided by placing red and white chevron signs, attached to tunnel walls to indicate a rather sharp curve and its direction. They can also be used to improve visual guidance in unlit tunnels and tunnels with a low level of illumination. Chevron signs would preferably be installed in the entrance zone since here the eyes still need to adapt to the decreased luminance level. Another way to improve visual

guidance in tunnels that may also increase the amount of ambient luminance inside a tunnel, is to use a light colour for the tunnel walls.

In summary, providing some extra information to support lane keeping and visual guidance and to improve anticipation on the course of the road is very important in road tunnels. Road markings can be used in this respect, with profiled road markings providing better visual but also auditive and tactile information. Especially in case of low luminance or a somewhat wet road surface, profiled road markings could be provided.

2.7 Emergency lay-bys and turning niches

The most common way to minimize the available space in tunnels is not to have an emergency lane inside tunnels, something that is generally not accepted for long stretches of motorway. The absence of an emergency lane does not only affect the proximity of the tunnel wall, with an indirect effect on traffic safety, but may also have direct effects on traffic safety. In case of emergencies, such as a car breakdown, not enough room may be available to clear the driving lanes. The absence of an emergency lane may also have an effect on the drivers' fear and uncertainty.

To prevent dangerous situations, to decrease the subjective uncertainty of drivers, and to reduce fear, it is important to have enough opportunity to stop inside a tunnel and good evacuation and escape possibilities, irrespective of whether this is realised by means of an emergency lane or other facilities. Although no behavioural or evaluative studies are available, providing stopping facilities inside a tunnel is important, as discussed in several tunnel design guidelines (Macnab et al., 1984; Public Road Administration, Directorate of Public Roads, 1990). Emergency lay-bys facilitate safe parking off the road, and can also be used to work on technical installations. When using emergency lay-bys instead of emergency lanes, some attention should be paid to the overview from this lay-by on the driving lanes. If a car has to leave the emergency lay-by, enough sight distance should be available to judge whether it is safe to merge into the traffic stream. In this respect, an emergency lane is much safer, since they may be used to accelerate in order to perform safer merging behaviour.

Besides providing emergency facilities for off the road parking in case of a car breakdown, a sufficient amount of evacuation facilities, for instance turning niches, should be provided for emergency evacuation of the tunnel (Public Road Administration, Directorate of Public Roads, 1990). Evacuation in tunnels can normally be carried out in two ways. In tunnels with 2-way traffic, drivers are warned of upcoming danger, for instance by traffic control management and turn inside the tunnel to drive out. In twin-bore tunnels, escape is made possible by entering the other tunnel tube through cross-galleries. Cross-galleries, as used in current tunnel design, are in most cases pedestrian cross-galleries, although the necessity for cross-galleries that can be used by vehicles can be considered. In case of motorway tunnels, the majority of tunnels consists of two (or more) separate tubes, at least one for each

direction. However, turning niches are also important in tunnels with separate tunnel tubes, because there is always the possibility that the cross-galleries cannot be used because of problems inside the centre of the tunnel. In that case turning niches will have to be used in each tunnel tube separately.

Emergency lay-bys and turning niches are to be illuminated in a special way to make them distinct from the rest of the tunnel and should not be built in a continuation of an outer curve or in the entrance zone. Providing good evacuation and escape possibilities may also decrease feelings of fear or discomfort.

In summary, to assure traffic safety both directly and indirectly, sufficient emergency facilities should be provided, for instance emergency lanes, emergency lay-bys and turning niches. This will limit disastrous effects in case of problems like a car breakdown, fire inside the tunnel or part of the tunnel collapsing. Besides this, drivers feel more comfortable if they know these facilities are provided. This last factor is important not only with respect to the indirect effects on traffic safety, but also with respect to the willingness of drivers to use tunnels. This is a factor that also plays a role since in the future, tunnels may be financed by means of tolling.

2.8 Entries and exits

One of the characteristics of current tunnel design is that besides lane changes, there is almost no lateral activity in terms of merging traffic, crossings and intersections. However, in the near future, some countries may consider building tunnels with exits and entries inside, or consider to build tunnels on roads that already contain exits or entries. For example, in the 'Ringenprojektet', Sweden plans to build an entire underground motorway network to replace motorways near Stockholm. With exits and entries in tunnels, some problems are expected to arise. Since entries and exits lead to merging behaviour that requires more attention to be put into the driving task, the possibility for anticipating these entries and exits is limited, and drivers do not really expect entries and exits in tunnels, some effects on safety may be expected. Besides this, due to the presence of the tunnel wall, the available space for these actions is limited, which also reduces safety margins. If the driving task requires more attention, and attention is not increased to a sufficient level, or if certain traffic situations occur unexpectedly, this may decrease traffic safety. Although a few entries and exits are already located in tunnels, no evaluations are available.

A special tunnel situation that has some relation with entries and exits in tunnels in terms of merging behaviour was planned by the Dutch Department of Transport when expanding the existing Benelux tunnel. The expansion would consist of two extra tunnel tubes with two lanes for each direction and a special one-lane tunnel tube in the middle of these tunnel tubes, that might be used in one direction in the morning, and in the other direction in the evening. This situation, that implies merging just after leaving the middle tunnel tube, was examined in a

driving simulator experiment by Theeuwes, Van der Horst, Hoekstra and Kaptein (1995). In order to reach the one-lane tunnel tube, people had to leave the ordinary road lanes, so some time before entering the tunnel drivers had to choose whether to use the normal tube or the middle one. At the end of the middle tube, people had to merge again into the two lanes of the main road. Driving behaviour was recorded and compared to driving behaviour in the regular tunnel tubes to see if this design led to unwanted or unacceptable driving situations. Results showed that overall there were no significant differences, but at the end of the single lane tube, the steering activity (Steering Activity Rate, SAR) was higher than the activity in the normal tunnel tube. This was explained by the preparation for driving out of the tunnel and merging into the normal traffic. It may very well be that this effect of increased steering activity is also found at exits and entries inside tunnels, the latter as a consequence of preparing for merging traffic.

In a second study, Kaptein, Theeuwes and Hoekstra (1995) looked in particular at the rather complicated situation in which drivers using the single lane tube needed to merge into the main traffic stream. The question was whether this merging situation was acceptable with respect to driving behaviour and whether people are prepared to use the single-lane tube given this special merging situation. Results showed that the need to merge into busy traffic did not prevent drivers from using this tube. Even when road users had to reach an exit within 600 m after the tunnel exit, which required them to make two lane changes, they chose equally for the single- and the two-lane tunnel tubes. Overall, the merging situation did not lead to any problems.

It must be noted that the findings of this study can only be partially generalized to evaluate entries or exits inside tunnels. Basically, standards for exits and entries on open motorways should also be applied to entries and exits in motorway tunnels. However, it is unclear whether, due to lighting conditions and limited available space, merging inside a tunnel would result in dangerous situations. A complicating factor is that in tunnels people do not really expect any merging traffic. If there would be some unexpected lateral activity, this might lead to a sudden change in behaviour such as deviations in lateral position or strong braking behaviour. Therefore, some thorough investigation is required before entries and exits inside tunnels can be included in regular tunnel design.

3 DISCUSSION AND CONCLUSIONS

This literature review identified a number of tunnel design characteristics that are crucial for tunnel design with respect to traffic safety.

A major factor influencing driving behaviour, and therefore possibly affecting driving safety, is the transition from open road to tunnel. Since tunnels are expensive and time consuming to build, dimensions of current tunnel design are often minimized. Since these minimal

dimensions are only accepted in tunnels, and not on open roads, there are rather abrupt changes when approaching or entering a tunnel. Abrupt changes in driving conditions may lead to sudden changes in driving behaviour. The most prominent change is the transition in the amount of luminance. Luminance levels inside tunnels are usually lower than the levels on open roads. This may cause problems while approaching the tunnel, since drivers cannot perceive any detail inside. When they enter the tunnel, it also takes some time before the eyes are adapted to the lower luminance level. These two phenomena may lead to dangerous situations since anticipation and perceptibility are limited and braking behaviour may result. Therefore, large differences between the luminance levels inside and outside the tunnel must be avoided. Besides the transition in luminance level, other variables are involved with the transition from open road to tunnel, such as smaller road width and absence of an emergency lane, causing perceived narrowness. Decreased manoeuvring space, due to proximity of the tunnel wall, smaller lanes or the absence of an emergency lane may result in changes in driving behaviour. This may result in increased steering activity since people may have more trouble keeping their vehicle within one lane, lateral displacements caused by the fear to hit the tunnel wall, and a reduction in driving speed. Since lateral displacements and reductions in driving speed may lead to interference with other traffic, it is important to have enough space available between the outer lanes and the tunnel walls. Generally speaking, tunnel dimensions should not be restricted, but if restrictions are necessary, transitions from open roads to tunnels must be rather smooth, though clearly perceivable to the driver. Gradual transitions provide the time to get used to the new driving situation and do not require or provoke sudden changes in driving behaviour.

Another factor that affects traffic safety is driver uncertainty. Increased driver uncertainty usually results in behavioural changes. This requires other drivers to pay attention to the driving task even more. Therefore it is important to design tunnels that have only a minimal effect on driver uncertainty. A tunnel design characteristic that is important with respect to driving speed is the preview on the longitudinal profile, with limited preview causing increased driver uncertainty. Providing good sight distances, thereby enabling anticipation of the course of the road and upcoming traffic situations, may reduce drivers' uncertainty. Good visual guidance and anticipation of the course of the road may for instance be realized by using profiled road markings and light coloured tunnel walls. The amount of curvature and gradient inside a tunnel is important in this respect, since they both decrease the possibility to look through the tunnel and reduce sight distances and anticipation. Whenever possible, tight curves, large gradients and short sight distances—especially when unexpected—should be avoided. It is not yet known if these values should be allowed to deviate from standards for open roads.

The amount of fear or discomfort, as experienced inside a tunnel by a proportion of the driving population, may also reduce traffic safety. This anxiety has to do with the possibility that the tunnel collapses and with limited possibilities for escape. Tunnels are constructed to overcome physical obstacles such as complicated traffic situations, mountains or rivers. There is a difference in perceived fear between these different kinds of tunnels. In case of underwa-

ter passes, the implications of a collapse may be much larger than in other cases and the possibility of leakage is perceived as frightening. It is important to provide good evacuation and escape possibilities in all tunnels, including the possibility for emergency stopping and turning around. Fear can also be reduced by means of traffic management systems and the provision of additional information in case of dangerous situations inside the tunnel, especially in long tunnels. People indicate to experience an increased amount of fear when driving long tunnels. Providing some additional information about the tunnel, for instance an indication of its total length, the remaining length, and a "tunnel safe" indication, may reduce this fear. A common indication is a warning in case of problems inside the tunnel, or the indication that only one driving lane is available. Besides indicating there is a problem, it may also be useful to think of an indication that the tunnel is safe. This will reduce fear of entering or driving inside a tunnel in two ways. First, a driver knows the tunnel is safe and secondly he also knows the tunnel is under observation, so in case of problems, this will be noticed immediately.

There are some tunnel design aspects that cause hindrance to drivers and may affect safety in that sense. The presence of a light flicker while entering the tunnel, for instance as a consequence of using sun screens or grids in the threshold zone, is experienced as very disturbing and may even lead to problems for epileptic drivers. Counterbeam lighting can also result in a flicker effect since it aims light in the direction of travel. Flicker effects must be avoided whenever possible. Another disturbing effect may arise by a high amount of stimulation in the visual periphery. If drivers choose a speed and position so that the value of 2 rad/s of angular velocity in the visual periphery is exceeded, they will experience this as very unpleasant and they will tend to slow down or choose a different lateral position. It is important to take this into account when designing tunnel walls and tunnel interior.

Finally, the complexity of the driving situation not only affects traffic safety in tunnels, but also traffic safety in general. If a traffic situation is more complex, for instance in case of merging traffic, exits and entries, a large amount of signs and markings, drivers have to divide their attention over more items, which may lead to unsafe driving conditions if there is an overload of information. Research shows that road users focus their attention on tunnel entrances about 150m before entering the tunnel. This means that the presence of a complex driving situation within the last 150m before the tunnel entrance may either distract the attention necessary for anticipating the tunnel entrance, or result in insufficient attention paid to surrounding traffic and the driving situation. Both situations may lead to a reduction in traffic safety. Therefore, in the last 150 metres before a tunnel entrance, the driving situation should not ask for any special attention.

With all these design factors it should be kept in mind that subjective dimensions of tunnel design may also affect safety. If tunnel design leads to the occurrence of visual illusions, such as a narrowing when it is not present, drivers are likely to respond in the same way as if the narrowing was actually there. Drivers should get a clear picture of the actual construction.

Also in terms of visual illusions, rather abrupt transitions in tunnel dimensions should be avoided.

4 RECOMMENDATIONS FOR FUTURE RESEARCH

There are only a relatively small number of studies available on the effects of tunnel design on driving behaviour. There are areas that are underrepresented whereas some important factors in tunnel design are not examined at all. In order to provide a complete basis for specific recommendations on future tunnel design standards, most aspects require supplementary investigation.

First of all, there is only a limited amount of research available on long tunnels and their specific effect on driving behaviour. Drivers indicate that driving in long tunnels is fearful, but the exact relation of tunnel length and traffic safety is not yet examined. Research is required that compares driving behaviour in long tunnels over different design characteristics and that examines possible behavioural changes as people drive in the tunnel for a longer time.

Second, standards for some design aspects such as gradients, curves and pavement width are less strict for tunnel design. It is yet unknown if these deviations are well-considered in terms of traffic safety.

Third, no experimental data are available on entries and exits in tunnels. Although some tunnels may already contain entries inside the tunnel tube, no studies are known that evaluate this situation. Designing exits and entries, or even intersections inside tunnel tubes may cause some problems. Restricted sight distances may prevent sufficient anticipation. Drivers do not (yet) expect merging traffic inside tunnels and building exits and entries in tunnels implies that extra road signs are required, to indicate an upcoming exit. This effect of extra information inside the tunnel will also have to be investigated.

Finally, not much research is available on fear or feelings of discomfort when driving in tunnels. Literature that is available does not contain any behavioural experiments, but is only descriptive where drivers indicate how they feel when driving in tunnels. Due to the absence of a thorough investigation, the exact effect of different design characteristics on the amount of fear or discomfort people experience is yet unclear.

An extensive examination of these factors is especially important since several European countries plan to build more and more tunnels, including tunnels of considerable length. This implies that in the near future, tunnels may have equally complicated traffic situations as open roads, including exits and entries. Design standards for motorway tunnels should indicate what standards for tunnel design should be applied and to what extent it is acceptable—in terms of traffic safety—to deviate from open road standards.

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15. **ABSTRACT (MAXIMUM 200 WORDS (1044 BYTES))**

Due to financial and technical considerations, the design of road tunnels often differs from open road design. Standards are applied more loosely, which leads to suboptimal design solutions in terms of traffic safety and comfort. This may affect the level of driving safety for instance if the design provokes sudden changes in driving behaviour, and does not permit sufficient anticipation.
This literature review provides an overview of the effect of tunnel design characteristics on road user behaviour, and can serve as a basis for recommendations on specific tunnel design standards. Various tunnel design characteristics are discussed with respect to their effect on driving behaviour. Tunnel entrances are of special interest, since they confront road users with the transition from open roads to tunnels. To provide safe driving conditions, precautions should be taken to make this transition as smooth as possible. Besides this, the amount of fear and discomfort drivers experience should be minimised and anticipation of upcoming traffic situations should be allowed. Although the focus is on tunnels on motorways, literature of tunnels on other road categories outside the built-up area is discussed as well to provide a more extensive view on tunnel related problems. The effects of lighting, proximity of tunnel wall, lane width, tunnel length, the longitudinal profile, road signs, road markings, emergency lay-bys, and entries and exits will be discussed successively in terms of their effect on driving behaviour. This knowledge can then be used to optimise current design criteria. Finally, an overview is provided of remaining issues that need thorough investigation in future research in order to come to optimal standards for tunnel design.

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